Quasar-Marked Protoclusters and Biased Galaxy Formation

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Abstract. We report on the current status of our search for protoclusters around quasars at $z > 4$. While the search is still very incomplete, clustered companion galaxies are found in virtually every case examined so far. The implied comoving number densities of protogalaxies are two to four orders of magnitude higher than expected for the general field, but are comparable to the number densities in rich cluster cores. The comoving densities of star formation in these regions are also enhanced by a comparable factor. We interpret these results as an evidence for biased galaxy formation in the highest peaks of the primordial density field.

1. Introduction

Our goal is to discover and study protogalaxies (PGs) clustered with known quasars at $z > 4$, perhaps in the cores of future rich clusters. This work complements the efforts by other groups to study galaxy formation in the general field, at the epochs when the universe was only a few percent of its present age. It also represents a powerful test of biased galaxy formation models.

PGs have been found using a variety of techniques: narrow-band Lyα imaging (Cowie & Hu 1998), Lyman-break method (Steidel *et al.* 1996), as DLA absorbers (Djorgovski *et al.* 1996), quasar companions (Hu *et al.* 1996, Djorgovski 1998), gravitationally lensed objects (Franx *et al.* 1997), serendipitously (Dey *et al.* 1998), etc. However, any single method has its own biases, and formative histories of galaxies in different environments may vary substantially. For example, galaxies in rich clusters are likely to start forming earlier than in the general field, and studies of galaxy formation in the field may have missed possible rare active spots associated with rich protoclusters.

We are conducting a systematic search for clustered PGs, by using quasars at $z > 4$ as markers of the early galaxy formation sites (ostensibly protocluster cores). The quasars themselves, selected from the DPOSS survey (Djorgovski *et al.* 1999; cf. also Kennefick *et al.* 1995), are purely incidental to this search: they are simply used as beacons, pointing towards the possible sites of early, massive galaxy formation. Our preliminary results are promising.

2.   Quasars as Markers of Early Galaxy Formation Sites

Statistical studies by Madau *et al.* (1996) and others have outlined a global history of galaxy formation in the general field, with a broad peak at $z \sim 2 - 3$. Steidel *et al.* (1998) have shown that the apparent decline at larger redshifts may not be real, and that considerable star formation goes on even at $z > 4$. Such PGs must be still very young, at most a few percent of the present galaxian age, or $\sim 0.5 - 1$ Gyr, for any reasonable cosmology. The current theoretical belief is that some subgalactic structures ($M \sim 10^6 - 10^8 M_\odot$) may start forming at $z \sim 6 - 10$, (e.g., Miralda-Escude & Rees 1997), and more massive ($M \sim 10^{11} - 10^{12} M_\odot$) PGs are expected to be very rare at $z > 4$, but there is still very little known empirically about galaxy formation at such redshifts.

Some of the first massive PGs may be the hosts of quasars at $z > 4$. The comoving density of quasars tracks well the history of star formation in galaxies, and both follow the merger rate evolution predicted by hierarchical structure formation scenarios. The same kind of processes, dissipative merging and infall, may trigger both star formation and the AGN activity. Most or all ellipticals and massive bulges at $z \sim 0$ seem to contain central massive dark objects suggestive of an earlier quasar phase (Kormendy & Richstone 1995, and references therein), whose masses correlate with the luminous old stellar masses of the host galaxies, suggesting that they formed coevally. The activity may mask the undergoing star formation, but AGNs may still provide useful pointers to the sites of early galaxy formation. High metallicities (up to $10 \times Z_\odot$!) observed in $z > 4$ quasars (Hamman & Ferland 1993) are indicative of a considerable chemical evolution involving several generations of massive stars in a system massive enough to retain and recycle their metals, comparable to the cores of giant ellipticals. Abundance patterns in the intracluster x-ray gas at lower redshifts are suggestive of an early, rapid star formation phase at high redshifts (Loewenstein & Mushotzky 1996). Quasars at $z > 4$ may thus be situated in the progenitors of future giant ellipticals and rich clusters.

In general, the most massive density peaks in the early universe are likely to be strongly clustered (Kaiser 1984; Efstathiou & Rees 1988) and thus the first galaxies may be forming in the cores of future rich clusters: the early formation of galaxies should be closely related to the primordial large-scale structure. This is a generic expectation in most models of galaxy formation. Such bias is already seen at $z \sim 3 - 3.5$ (Steidel *et al.* 1998), and it should be even stronger at $z > 4$. It then makes sense to look for other galaxies, with or without AGN, forming in the immediate vicinity of known $z > 4$ quasars. We note that the quasars themselves are purely incidental to this project: we simply want to use them as markers of the likely galaxy formation hotspots in the early universe.

3.   Some Preliminary Results

This approach has been proven to work. A Lyα galaxy and a dusty companion of BR 1202–0725 at $z = 4.695$ have been discovered by several groups. (Djorgovski 1995, Hu *et al.* 1996, Petitjean *et al.* 1996), and a dusty companion object has been found in the same field (Omont *et al.* 1995, Ohta *et al.* 1995). Hu &

McMahon (1996) also found two companion galaxies in the field of BR 2237–0607 at $z = 4.55$.

We have searches to various degrees of completeness in about twenty QSO fields so far (Djorgovski 1998; Djorgovski *et al.*, in prep.). Companion galaxies have been found in virtually every case, despite very incomplete coverage. They are typically located anywhere between a few arcsec to tens of arcsec from the quasars.

Some are close projected companions near the lines of sight to quasars, selected by simple deep R-band imaging and confirmed using long-slit spectroscopy. This method probes $\sim 100+$ comoving kpc scale environments of quasar hosts, which are likely still forming through dissipative merging of protogalactic clumps.

We also select candidate PGs associated and/or clustered with quasars by using deep BRI imaging over a field of view of several arcmin, probing ~ 10 comoving Mpc ($\sim$ cluster size) projected scales. These imaging data are obtained at the Palomar 200-inch and the Keck-II 10-m telescope. This is a straightforward extension of the method employed so succesfully to find the quasars themselves at $z > 4$ (at these redshifts, the continuum drop is dominated by the Lyα forest, rather than the Lyman break, which is used to select galaxies at $z \sim 2 - 3.5$). The candidates would then be followed by multislit spectroscopy at the Keck.

As of the mid-1999, about two dozen companion galaxies have been confirmed spectroscopically, with a comparable number still in progress (the usual reason: more integration needed). Their typical magnitudes are $R \sim 25^m$, implying continuum luminosities $L \leq L_*$. The Lyα line emission is relatively weak, with typical restframe equivalent widths $\sim 20 - 30$ Å, an order of magnitude lower than what is seen in quasars and powerful radio galaxies, but perfectly reasonable for the objects powered by star formation. There are no high-ionization lines in their spectra, and no signs of AGN. The SFR inferred both from the Lyα line, and the UV continuum flux is typically $\sim 5 - 10\ M_\odot$/yr, not corrected for the extinction, and thus it could easily be a factor of 5 to 10 times higher.

Overall, the intrinsic properties of these quasar companion galaxies are very similar to those of the Lyman-break selected population at $z \sim 3 - 4$, except of course for their special environments and somewhat higher look-back times.

There is a hint of a trend that the objects closer to the quasars have stronger Lyα line emission, as it may be expected due to the QSO ionization field. In addition to these galaxies where we actually detect (presumably starlight) continuum, pure Lyα emission line nebulae are found within $\sim 2 - 3$ arcsec for several of the quasars, with no detectable continuum at all. The Lyα fluxes are exactly what may be expected from photoionization by the QSO, with typical $L_{Ly\alpha} \sim$ a few $\times 10^{43}$ erg/s. They may represent ionized parts of still gaseous protogalaxy hosts of the quasars. We can thus see and *distinguish* both the objects powered by the neighboring QSO, and "normal" PGs in their vicinity.

The median projected separations of these objects from the quasars are $\sim 100 h^{-1}$ comoving kpc, an order of magnitude less than the comoving r.m.s. separation of L_* galaxies today, but comparable to that in the rich cluster cores. The frequency of QSO companion galaxies at $z > 4$ also appears to be an order of magnitude higher than in the comparable QSO samples at $z \sim 2 - 3$, the peak

of the QSO era and the ostensible peak merging epoch. However, interaction and merging rates are likely to be high in the densest regions at high redshifts, which would naturally account for the propensity of some of these early PGs to undergo a quasar phase, and to have close companions.

The implied average star formation density rate in these regions is some 2 or 3 orders of magnitude higher than expected from the limits estimated for these redshifts by Madau *et al.* (1996) for *field* galaxies, and 1 or 2 orders of magnitude higher than the measurements by Steidel *et al.* at $z \sim 4$, even if we ignore any SFR associated with the QSO hosts (which we cannot measure, but is surely there). These really are regions of an enhanced galaxy formation in the early universe.

4. Concluding Comments

Our survey is still very incomplete, but there is already a clear indication of an "excess" of PGs in these fields. This may be an observable manifestation of biasing, i.e., the expected clustering of the highest density peaks. The same explanation applies to the Steidel *et al.* redshift "spikes" at $z \sim 3 - 3.5$; what we are looking for are even denser, and thus much rarer peaks at $z > 4$. Because they are rare, we use quasars as markers of sites where some structure is already forming, in order to increase our chances. A "pure deep field" approach at these redshifts is much harder and would likely yield fewer objects than at $z \sim 3$. These quasar fields are obviously very special spots in the early universe, and they present a great opportunity to study galaxy and cluster formation, in an enviroment deliberately different from the general field.

It is also worth noting that (perhaps coincidentally) the observed comoving number density of quasars at $z > 4$ is roughly comparable to the comoving density of very rich clusters of galaxies today. Of course, there must be some protoclusters without observable quasars in them, and some where more than one AGN is present.

Finally, there is some evidence for the clustering of quasars themselves, on scales $\sim 100 \ h^{-1}$ comoving Mpc (cf. Djorgovski 1998). This is an interesting scale, corresponding to the excess power seen in some of the redshift surveys (e.g., Broadhurst *et al.* 1990; Landy *et al.* 1996) and also close to that of the first Doppler peak in the CMBR. This effect may be an artifact of a variable depth of the survey (something that we can and will test in the future). It may also be due, e.g., to a patchy gravitational lensing magnification by the foreground large-scale structure; again, we can test this hypothesis using the DPOSS galaxy counts. Finally, the effect may be due to a genuine (super)clustering of the highest peaks of the primordial density field, some of which happen to be decorated with luminous quasars. This would be a natural, albeit remarkable, extension of the basic concept of biased structure formation in the early universe.

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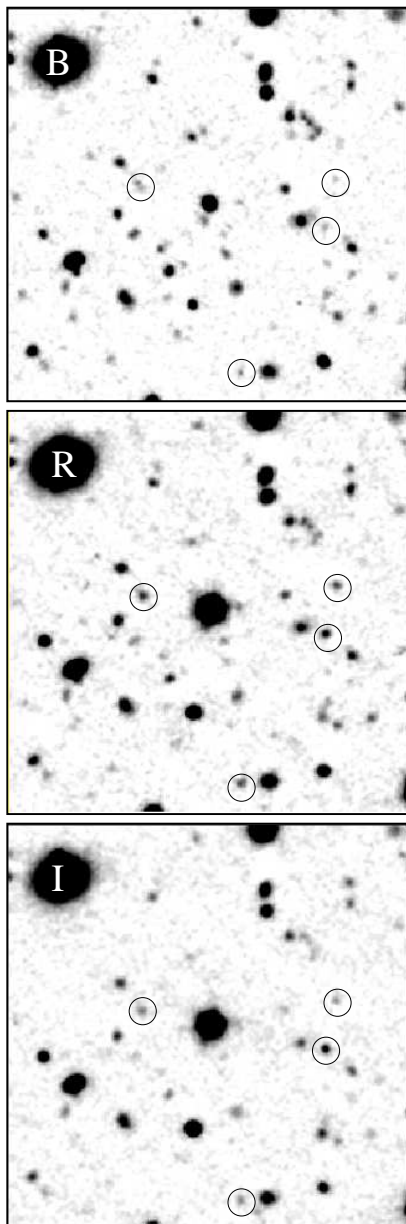
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Figure 1. Keck images of a field centered on the quasar PSS 2155+1358, at $z = 4.26$, in BRI (top to bottom). The field shown is approximately 54 arcsec square, and is centered on the quasar. Several color-selected objects are circled; they are likely companion PGs clustered with the quasar.